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Longitudinally diode-pumped Nd:YAG double-clad planar waveguide laser.

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Abstract

We report the demonstration of a near-diffraction-limited, compact, diode-end-pumped double-clad planar waveguide Nd:YAG laser. Efficient laser operation was achieved for the three dominant Nd^{3+} transitions at 1.064μm, 0.946μm, and 1.32μm, with TE polarised output powers of 1.33W, 0.57W, and 0.33W for the available output couplers. The output beam from the monolithic plane-plane laser cavity had measured M^2 values of 1.0 and 1.8, perpendicular and parallel to the plane of the waveguide respectively.

Planar waveguides are well suited to acting as the host structure for diode-pumped solid-state lasers, due to a combination of features related to their slab-like geometry. The use of a planar end-pumped gain region avoids the need to use beam-shapers or brightness-reducing fibre coupling to circularise the normally asymmetric diode pump beam. The slab shape also offers good thermal management and consequent prospects for power scaling. These attractive features have been studied in recent work on bulk lasers [1-3], and can be taken to their extreme in the case of a planar waveguide where, if the numerical aperture of the waveguide is high enough, the diode can simply be proximity-coupled [4]. This pumping scheme lends itself to side-pumping with diode-bars of several tens of Watts output power, and recent results have demonstrated >12W continuous wave (cw), and >8W passively Q-switched, waveguide laser output [5]. The output beam of the side-pumped waveguide laser is diffraction-limited in the fast divergence axis due to the use of a double-clad waveguide [4,5], however, for a plane-plane monolithic laser resonator, the slow axis is highly multi-mode. In this paper we describe end-pumping of similar double-clad waveguides by a 4W broad-stripe diode leading to near-diffraction limited output in both dimensions at output powers of greater than 1W. The prospects for scaling to higher powers are also discussed.

The Nd:YAG waveguide used in this experiment is the same as that described in [4] and is shown schematically in figure 1. The 5-layer double-clad structure was fabricated by Onyx Optics, Inc., using the direct-bonding method. The waveguide structure consisted of a weak inner guide formed by a 20μm-thick neodymium-doped YAG core (1at.% Nd), between two 5μm-thick un-doped YAG layers, the inner cladding. Two 4mm-thick sapphire layers formed the outer cladding and provide excellent thermal conduction away from the doped core. The neodymium doping in the core provides a refractive index increase, $\Delta n \approx 0.0004$, with respect to the un-doped cladding, leading to a numerical aperture (NA) ≈ 0.04. A greater refractive index difference is present between the sapphire and YAG, $\Delta n \approx 0.06$, giving an NA $\approx$ 0.46. Due to the desire to keep the pump absorption length small, the doped core to un-doped inner cladding ratio is relatively large compared to standard optical fibre designs. Thus the core is not optically isolated from the outer cladding and so the propagation modes of the overall multi-mode 5-layer structure must be considered. However, as the fundamental mode reaches threshold first, and has a high intensity over the central doped region, it will saturate most of the available gain preventing the higher-order modes from achieving threshold, leading to a diffraction-limited output in the guided axis.

The propagation loss of the waveguide was investigated by end-pumping with a Ti:sapphire laser, and measuring the 1.064μm laser threshold for a variety of output couplers [4]. The insert on figure 2 shows the results for laser cavities consisting of two highly-reflecting (HR) mirrors, one HR and one end-face Fresnel reflection (~8%), and two Fresnel reflections. The loss value is obtained from the intercept on the x-axis, for which the percentage error could be rather large. Nevertheless the intercept clearly indicates a low-loss, equivalent to a few tenths of a dB/cm. In order to confirm this value the output slope efficiency was also measured and found to be as high as 51% when using a R=82% output coupler (fig.2). The upper limit for the slope efficiency is given by

$$\eta \le \frac{\lambda_p}{\lambda_l}\left(\frac{-\ln R}{L-\ln R}\right) \qquad \ldots(1)$$

where λ_p and λ_l are the pump and laser wavelengths and L represents the other round-trip cavity losses. Thus we can put an upper limit on L of 0.1 which corresponds to 0.2dB/cm and agrees well with previously found values for direct-bonded waveguides [4].

Figure 3 shows the experimental set-up used for the diode-pumping experiments. The source used was a 4W cw broad-stripe single-emitter laser diode from Boston Lasers. The diode had an emission area of 1 x 200 μm^2 and was fibre-lensed to collimate the fast axis. The diode spectrum had a width of ~1.5nm which, when used to pump the double-clad structure, led to a measured absorption coefficient of ~2cm^{-1}. The beam quality, measured with a Coherent Mode Master, was found to be M_y^2 = 3.2±0.1 and M_x^2=39±1, in the fast and slow axes respectively. The laser diode output was coupled into the double-clad waveguide via two cylindrical lenses of focal lengths f_x=19mm and f_y=12.7mm for the slow and fast axes respectively, chosen through optimisation of the waveguide laser power. The corresponding calculated pumping spot size (second moment radius) for the unguided plane was 57μm, whereas the guided pumped dimension is set by the 20μm-deep doped core. The positions of the lenses and waveguide were also optimised for best output power performance.

The laser resonator was formed by dielectric mirrors held onto the end-faces of the waveguide via the surface tension of a very thin layer of fluorinated liquid. The end-faces of the waveguide had been polished parallel such that the mirrors formed a monolithic plane-plane cavity, 10mm in length. For each laser transition studied the input mirror was HR at the lasing wavelength and had high transmission for the pump wavelength. Only a limited number of output coupler mirrors were available for the two weaker transitions, $^4F_{3/2} \rightarrow {}^4I_{9/2}$ ($\lambda_l \doteq 946$nm), and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ ($\lambda_l = 1.32$ µm), where selection was based on achieving a lower laser threshold with respect to the dominant transition, $^4F_{3/2} \rightarrow {}^4I_{11/2}$ ($\lambda_l = 1.064$µm). In contrast, for the $\lambda_l = 1.064$µm transition, a wide range of output coupler mirrors were available allowing a true optimisation for maximum waveguide laser output power. The output couplers used for each transition were: $\lambda_l = 1.064$µm, $T_{o/c}$=32%; $\lambda_l = 946$nm, $T_{o/c}$=3%; $\lambda_l = 1.32$ µm, $T_{o/c}$=7%.

Figure 4 illustrates the laser output power results as a function of the incident diode pump power. It can be seen that a maximum 1.064µm output power of 1.33W was obtained for 3.8W of incident pump power, corresponding to an optical to optical conversion efficiency of 34%. The slope efficiency cannot be calculated directly from figure 4 as the wavelength of the diode was seen to vary significantly with current, and hence output power. However, the best absorption of ~2cm^{-1} was obtained at the maximum output power. A Coherent Mode Master was again used to measure the laser beam quality, which was found to be $M_y^2 = 1.0 \pm 0.1$ and $M_x^2 = 1.8 \pm 0.1$ for an output power of 1.25W. Using a Cohu CCD camera and Coherent BeamView Analyser, a beam profile was recorded, from which the beam 1/e^2 intensity radii at the output mirror were determined to be $W_y = 10 \pm 1$µm and $W_x = 165 \pm 5$µm. Thus the laser beam is well collimated over the cavity length and is larger than the pump beam over a distance comparable to one absorption length assuming that the pump waist is inside the gain medium, as would be expected for optimum performance. It is possible that further optimisation of the non-guided pumping spot size could have lead to a slightly lower M^2 value in this plane. Thermal lensing effects, typical for high power diode-pumped lasers, would effectively produce aberrated cylindrical lenses of different focal lengths in the two axes of the waveguide [3,6]. In bulk systems with planar gain regions, the dominant lens is in the tightly focussed axis. In the case of a waveguide this is the guided axis and the optical confinement appears to overcome any possible adverse effects at the power levels investigated here. The effect of any thermal lensing in the less tightly focussed, non-guided plane has not as yet been quantified and future work will investigate this feature, especially for higher-power operation, such that it may be incorporated into the laser cavity design [3]. It should be noted that the relatively high output beam asymmetry could be easily circularised with cylindrical lenses if required. The laser output was found to be nearly linearly polarised with a ratio in power of approximately 9 to 1 between TE and TM states. This unexpected polarisation behaviour has previously been observed in both Nd and Yb doped double-clad direct-bonded waveguides [4].

A lower maximum output power of 0.57W (for 3.5W incident power) was observed for the quasi-three level transition, λ_l = 946nm, as shown in Figure 4. This lower efficiency was the result of using a higher-reflectance output coupler. The use of output coupling nearer to the 30% value used for the 1.064μm lasing is certainly possible and would significantly improve the conversion efficiency. Finally for the λ_l = 1.32 μm transition the output power was lower again (0.33W for 3.5W incident power), despite using a larger output coupling than for the 946nm lasing. This is, at least in part, due to the larger quantum defect.

By relating the numerical aperture of a waveguide to the divergence angle of a beam passing through an equivalent aperture, we can calculate the maximum allowed pump M^2 value that can be contained by a double-clad waveguide as

$$M^2 \approx D\sin^{-1}(NA)/\lambda \qquad \ldots(2)$$

where D is the width of the core and inner cladding and NA is the numerical aperture of the outer cladding to inner cladding. Thus M^2 values of ~17 could be confined by the current 5-layer waveguide design. This may allow a higher-power pump source to be used, which has an inferior beam quality compared to the diode used here. Typical fibre-coupled diode-bars have M^2 values of ~60 which would require a guide with D~100μm for the current NA. If a design based on a higher-NA guide were used then lower values of D become possible. For instance a GGG/sapphire composite would have an NA of 0.86 and a required D value of just ~50μm, close to that used here. A more straightforward scaling of the output power of this laser to a few Watts should also be possible by polarisation-coupling two broad-stripe diode sources for single-ended pumping. Further performance improvements could be expected if the crystal facets were directly coated with dielectric mirrors rather than the butted mirrors used for convenience in these experiments.

In conclusion, we have demonstrated a simple longitudinally-pumped double-clad planar Nd:YAG waveguide laser with 1.33W output power at 1.064μm, in a near-diffraction-limited beam, $M^2 = 1.0 \times 1.8$. Laser action was also demonstrated for the weaker 946nm and 1.32μm transitions. Output powers of 570mW and 330mW were measured respectively and improved performance for these transitions can be expected with optimised mirrors. The simplicity, excellent thermal properties, efficiency, and robust design of this device make it an attractive candidate for multi-Watt diffraction-limited performance for a range of laser wavelengths. Scaling to higher powers using fibre-coupled diode-bar pump sources also appears feasible for a modified double-clad waveguide design.

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Figure Captions.

Figure 1: Schematic of the double-clad waveguide geometry

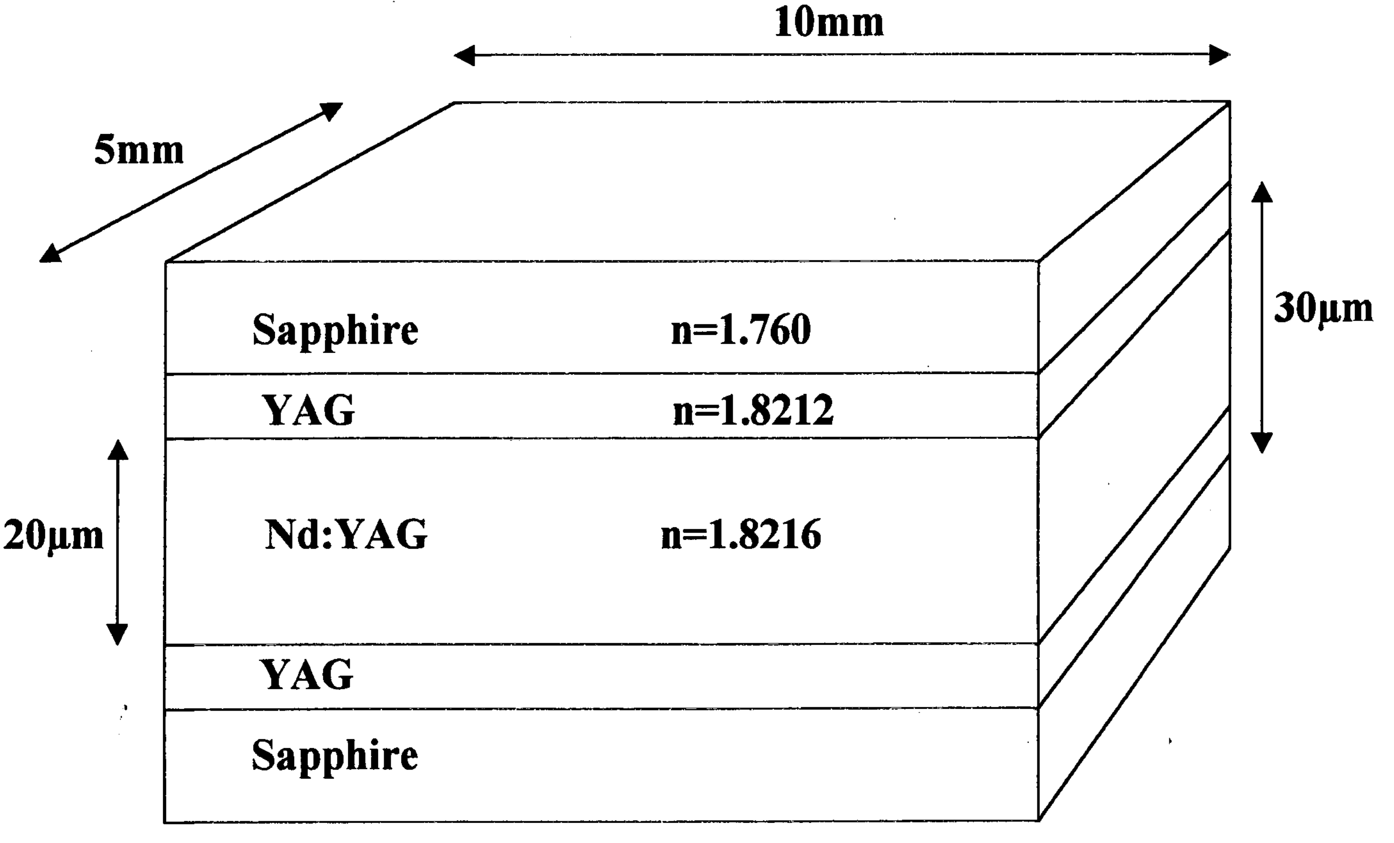
Figure 2: Plot of output power versus absorbed pump power for the Ti:sapphire pumped waveguide laser. Inset is a plot of threshold incident pump power versus output coupling.

Figure 3: Diagram of the diode end-pumping arrangement.

Figure 4: Plot of the diode-pumped waveguide laser output power versus incident pump power for three transitions in Nd:YAG.

References

1. D. Kopf, U. Keller, M. A. Emanuel, R. J. Beach, and J. A. Skidmore, Opt. Lett., **22**, 99 (1997).
2. K. Du, N. Wu, J. Xu, J. Giesekus, P. Loosen, and R. Poprawe, Opt. Lett., **23**, 370 (1998).
3. J. L. Blows, G. W. Forbes, and J. M. Dawes, Opt. Comm., **186**, 112 (2000).
4. C. L. Bonner, T. Bhutta, D. P. Shepherd, and A. C. Tropper, IEEE J. Quantum. Electron., **QE-36**, 236 (2000).
5. R. J. Beach, S. C. Mitchell, H. E. Meissner, O. R. Meissner, W. F. Krupke, J. M. McMahon, and D. P. Shepherd, submitted to Opt. Lett. (2000).
6. J. M. Eggleston, T. J. Kane, K. Kuhn, J. Unternahrer, and R. L. Byer, IEEE J. Quantum Electron., **QE-20**, 289 (1984).


10mm
5mm
30µm
20µm
Sapphire
n=1.760
YAG
n=1.8212
Nd:YAG
n=1.8216
YAG
Sapphire

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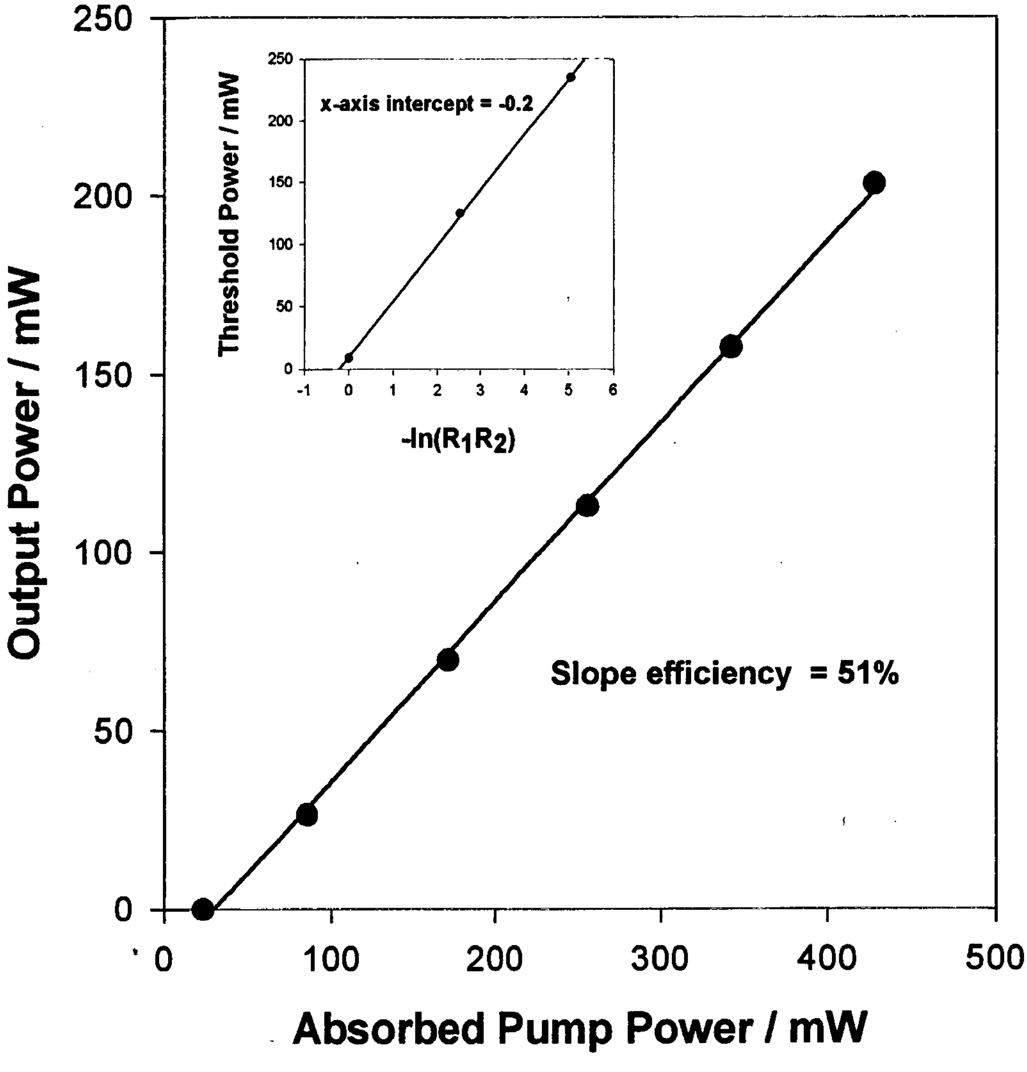

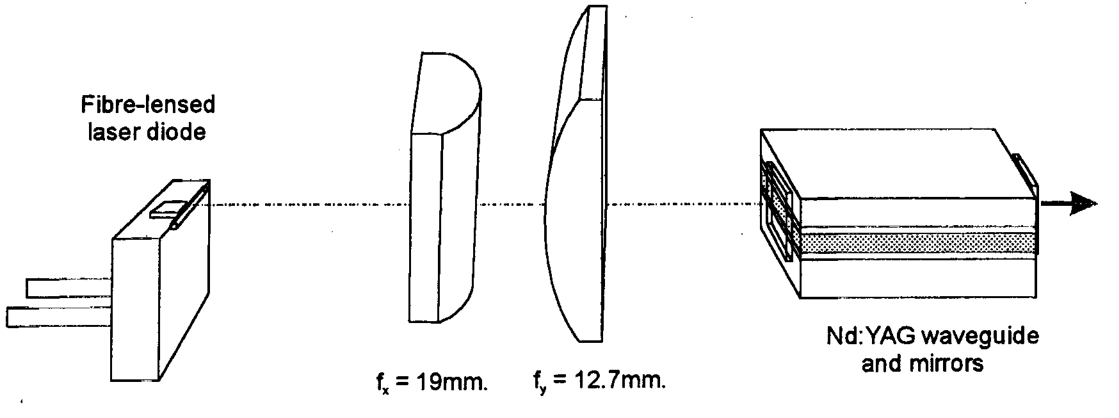
Fibre-lensed
laser diode
f_x = 19mm.
f_y = 12.7mm.
Nd:YAG waveguide
and mirrors